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Status of solar desalination in India

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ABSTRACT

The work was motivated by the increasing awareness of the need for enhancing water supplies schemes in arid lands featuring an appropriate technology for solar energy use in the desalination field in India. The fresh water crisis is already evident in many parts of India, varying in scale and intensity at different times of the year. India's rapidly rising population and changing lifestyles also increases the need for fresh water. Fresh water is increasingly taking centre stage on the economic and political agenda, as more and more disputes between and within states, districts, regions, and even at the community level arises. The conventional desalination technologies like multi stage flash, multiple effect, vapor compression, iron exchange, reverse osmosis, electro dialysis are expensive for the production of small amount of fresh water, also use of conventional energy sources has a negative impact on the environment. Solar distillation represents a most attractive and simple technique among other distillation processes, and it is especially suited to small-scale units at locations where solar energy is considerable. India, being a tropical country is blessed with plenty of sunshine. The average daily solar radiation varies between 4 and 7 kWh per square meter for different parts of the country. There are on an average 250–300 clear sunny days in a year, thus it receives about 5000 trillion kWh of solar energy in a year. In spite of the limitations of being a dilute source and intermittent in nature, solar energy has the potential for meeting and supplementing various energy requirements. Solar energy systems being modular in nature could be installed in any capacity as per the requirement. This paper consists of an overall review and technical assessments of various passive and active solar distillation developments in India. This review also recommended some research areas in this field leading to high efficiency are highlighted.

Contents

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1. Introduction

The fresh water crisis is already evident in many parts of India, varying in scale and intensity at different times of the year. The fresh water crisis is not the result of natural factors, but has been caused by human actions. India's rapidly rising population and changing lifestyles also increases the need for fresh water. Intense competition among competing user's agriculture, industry and domestic sector is driving the ground water table deeper and deeper. Widespread pollution of surface and groundwater is reducing the quality of fresh water resources. Fresh water is increasingly taking centre stage on the economic and political agenda, as more and more disputes between and within states, districts, regions, and even at the community level arises. Nearly one million children in India die of diarrhea diseases each year directly because of drinking unsafe water and living in unhygienic conditions. Some 45 million people are affected by water quality problems caused by pollution, by excess fluoride, arsenic, iron or by the ingress of salt water. Millions do not have adequate quantities of safe water, particularly during the summer months. In rural areas, women and girls still have to walk long distances and spend up to four hours every single day to provide the household with water [1]. Scarcity of fresh water problems are facing many arid zones of Gujarat and Rajasthan, luckily these places are getting more amount of solar energy, apart Gujarat and Rajasthan that in western India, which face water shortage and have huge under ground saline water sources, certain regions in Haryana state and Maharastra states also have under ground saline water in spite of high rain fall [2].

R.K. Khanna et al. [3] studied in details about quality and availability of drinking water in a village Chui, Rajasthan. The village peoples are facing lot of difficulties to get fresh water for their family needs. All families the women and children are responsible for collecting and storage of water. The quality of drinking water also not suitable for human health, it was found by tested the village water samples at Guru Kripa test house at Ajmer district. After analyzing in all the aspects authors concluded that, the village peoples are expecting suitable low cost purification devices for getting pure drinking water. Desalination of brackish water and seawater to provide the deeded drinking water fulfills a basic social need and it does this without any serious impact on the environment. The conventional desalination technologies like multi stage flash, multiple effect, vapor compression, iron exchange, reverse osmosis, electro dialysis are expensive for the production of small amount of fresh water, also use of conventional energy sources has a negative impact on the environment. Solar distillation provides partially support humanity's needs for fresh water with free energy, simple technology and clean environment. Solar stills have a good chance of success in India for lower capacities which are more than 20 km away from the source of fresh water and where the TDS of saline water is over 10,000 ppm or where seawater is to be desalted [4].

India, being a tropical country, is blessed with plenty of sunshine. The average daily solar radiation varies between 4 and 7 kWh per square meter for different parts of the country. There are on an average 250–300 clear sunny days a year. Thus, it receives about 5000 trillion kWh of solar energy in a year. The annual global radiation varies from 1600 to 220 kW/m^2. The highest annual global radiation is received in Rajasthan and northern Gujarat. In spite of the limitations of being a dilute source and intermittent in nature, solar energy has the potential for meeting and supplementing various energy requirements Solar energy systems being modular in nature could be installed in any capacity as per the requirement. This paper presents of an overall review and technical assessments of various passive and active solar distillation systems in India. The assessment also recommended some research areas in the field of solar distillation, leading to high efficiency are highlighted and finally expressed the economic analysis of solar stills briefly.

2. Historical background of solar distillation

Distillation has long been considered a way of making salt water drinkable and purifying water in remote locations. As early as the fourth century B.C., Aristotle described a method to evaporate impure water and then condense it for potable use. Arabian alchemists were the earliest known people to use solar distillation to produce potable water in the sixteenth century. However, the first documented reference for a device was made in 1742 by Nicolo Ghezzi of Italy, although it is not known whether he went beyond the conceptual stage and actually built it. The first modern solar still was built in Las Salinas, Chile, in 1872, by Charles Wilson. It consisted of 64 water basins (a total of 4459 square meters) made of blackened wood with sloping glass covers. This installation was used to supply water (20,000 L/day) to animals working mining operations. After this area was opened to the outside by railroad, the installation was allowed to deteriorate but was still in operation as late as 1912–40 years after its initial construction. This design has formed the basis for the majority of stills built since that time.

During the 1950s, interest in solar distillation was revived, and in virtually all cases, the objective was to develop large centralized distillation plants. In California, the goal was to develop plants capable of producing 1 million gallons, or 3775 cubic meters of water per day. However, after about 10 years, researchers around the world concluded that large solar distillation plants were too much expensive to compete with fuel-fired ones. Therefore, research shifted to smaller solar distillation plants. In the 1960s and 1970s, 38 plants were built in 14 countries, with capacities ranging from a few hundred to around 30,000 L of water per day. Of these, about one third have since been dismantled or abandoned due to materials failures. None in this size range is reported to have been built in the last 7 years.

Despite the growing discouragement over community-size plants, McCracken Solar Company in California continued its efforts to market solar stills for residential use. Worldwide interest in small residential-units is growing, and now that the price of oil is ten times what it was in the 1960s, interest in the larger units may be revived. Although solar distillation at present cannot compete with oil-fired desalination in large central plants, it will surely become a viable technology within the next 100 years, when oil supplies will have approached exhaustion.

Table 1
Large size solar still installations put up by Central Salt & Marine Chemicals Research Institute, Bhavnagar (India) [4].

No.	Location	Capacity (L/day)	Evaporating area (m^2)	Year of installation	Quality of saline water	Present status and other remarks
1	CSMCRI Salt works, Bhavnagar	1000	350	1965	Seawater	Pilot plant supplied drinking water to labourers m salt works Damaged during heavy rams m 1968
2	Navinar Lighthouse near Mundra, Gulf of Kutch	130	49.9	1968	Seawater	Needs repairs but still working Supplies drinking water to staff members
3	Awania village, near Bahvnagar	5000	1866.6	1977/78	Saline well water TDS 3000–4500 ppm, fluoride 10 ppm	Supplies drinking water to village Extensively damaged by cyclone in November 1982 Windmill and solar cell pump used for water pumping Repaired and recommissioned in October 1984
4	Chhachl Lighthouse near Mandvi, Gulf of Kutch	250	108.0	1978/79	Seawater	Needs major repairs Not properly maintained Damaged by stray dogs, etc.
5	Narayana Sarovar, District Kutch, GuJarat	3000	1244.4	1983	Saline well water, TDS 15,000 ppm	Work started m 1977 but due to lack of saline water discontinued Out of 60 Stills, 46 were commissioned in winter 1983, using saline water from new source Raw water supply discontinued in 1985 and nobody took over the plant Project abandoned in 1987
6	Bhalen, District Churu, Rajasthan	8000	3110.0	1979	Saline well water, TDS 3800 ppm, nitrates 340 ppm, fluoride 4–5 ppm	Constructed by PHED, Rajasthan. Faces problems of supply of saline water for operating entire plant Windmill for pumping saline water
7	Bitra Island, Union territory of Lakshdweep	2000	750.0	1983	Seawater	Constructed by PWD Provides drinking water to islanders

3. Developments of solar distillation in India

The first largest solar distillation plant was installed by Central Salt and Marine Chemical Research Institute (CSMCRI), Bhavnagar to supply drinking water in Awania village and Chhachi lighthouse in 1978. Awania is a non electrified village about 12 km from Bhavnagar with a population around 1400. Fig. 1 shows the Awania plat layout. It consists of 90 stills each having evaporating surface of 20.74 m^2 equally distributed in 15 blocks having external dimensions of 12.66 m $\times$ 12.11 m with capacity of 5000 L/day. G.L. Natu et al. [5] gave their operation experiences at Awania village distillation plant. The villagers took some time to understand the difference between the quality of water produced by solar distillation plant and water from well after that they are using plant water regularly. The authors indicated that, smaller plants serving smaller communities will be the right application of this technology in India. Some of the majorities of high capacity solar still plants in India were installed by the Central Salt and Marine Chemical Research Institute (CSMCRI) given in Table 1 [4].

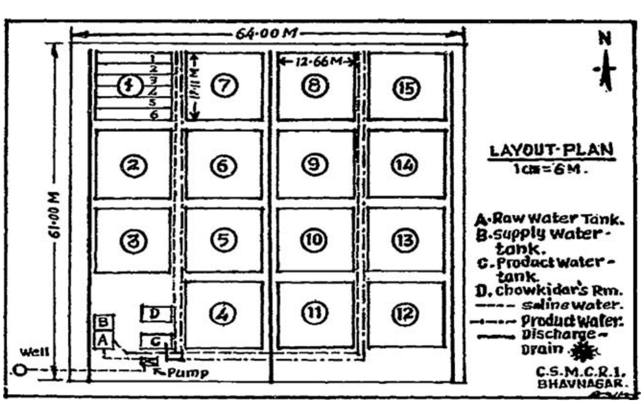

Fig. 1. Lay-out of solar distillation plant at Village Awania [5].

A first double slope solar distillation unit was installed (Fig. 2) with capacity of 85 L/day at IIT, Delhi, in January 1981, to meet the requirements of the Chemistry Department. The unit consists of 28 multi wick solar stills each of 1 m^2 effective area with four stills in a row. Each row of stills has independent feeding water pipes connected to a small storage tank. Due to high wind speed, power shortage, algae formation, etc., the plant was dismantled in June 1982 and reinstalled in October 1982 with some improvements [6].

The performance and the daily production of the solar still can be increased by various passive methods such as lowering water capacity in the basin, adding various dyes in the water mass, increasing the absorbtivity by providing various absorbing materials on the basin liner, extracting reflection radiation by fixing reflector on the inner wall surfaces, reducing conductive heat losses from sides, etc. It could also be improved through active methods of integrating the still with flat-plate collector, heat exchanger, etc. The classification of these development techniques addresses and summarized below.

3.1. Simple passive solar stills

Passive system in which solar energy collected by structure elements (basin liner) itself for evaporation of saline water. The simple single slope solar still is shown in Fig. 3. The sun's energy in the form of short electromagnetic waves passes through a clear glazing surface such as glass. Upon striking a darkened surface, this light changes wavelength, becoming long waves of heat, which is added to the water in a shallow basin below the glazing. As the water heats up, it begins to evaporate. The warmed vapor rises to a cooler area. Almost all impurities are left behind on the basin. The vapor condenses onto the underside of the cooler glazing and accumulates in to water droplets or sheets of water. The combination of gravity and the tilted glazing surfaces allows the water to run down the cover and into a collection trough, where it is channeled in to storage.

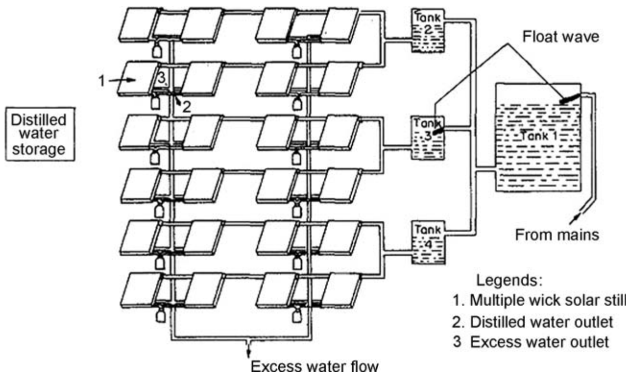

Fig. 2. Layout plan of solar distillation plant at IIT, Delhi [6].

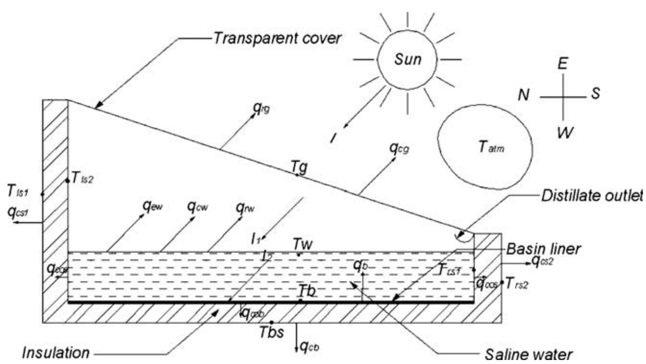

Fig. 3. Various components of single slope passive solar still.

3.2. Effect of water capacity and inclusion of dyes

On the basis of year round performance of solar still under Indian climatic conditions, H.P. Garg and H.S. Mann [7] concluded that, (i) a lower glass-cover angle gives higher output (ii) for high altitude stations the long axis of the conventional double sloped still should face an east–west direction in order to receive more solar radiation, (iii) a single sloped solar still receives more radiation than a double sloped solar still at low and high altitude stations (iv) the productivity of a still increases with the decrease in water depth, increasing the absorptivity of water by using dyes and increasing initial water temperature by using preheated water. G.N. Tiwari and Madhuri [8] studied the effect of initial water temperature on the distillation output, and they found that, the yield increases when the initial water temperature of the brine greater than 45 °C. Rajesh Tripathi, G.N. Tiwari [9] indicated that, the change in the length of a solar still for given height and width of a solar still does not affect the daily output but the change in the height of the north wall for a given height of the solar still affects the daily output. Anil Kr. Tiwari, G.N. Tiwari [10], found the evaporative heat transfer depends significantly on water depths and the nocturnal distillation is significant in the case of higher water depths.

3.3. Still with cover cooling and water flow in the basin

The productivity of the still is mainly depends on the temperature difference between water and condensing cover. This difference is high will get more output. This can be achieved by either increasing the basin water temperature or decreasing the cover temperature or both. These techniques are summarized below. G.N. Tiwari and V.S.V. Bapeshwara Rao [11] studied the effect of cooling water flowing over the glass (Fig. 4) and its velocity. The result shows that, water flowing over glass cover at a uniform velocity, the daily distillate production of the system is almost doubled.

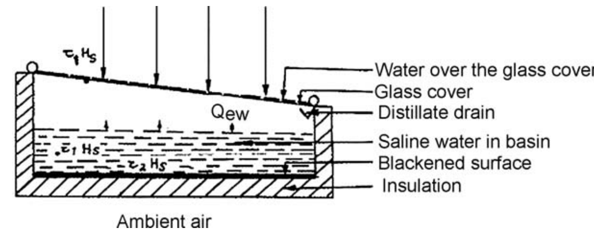

Fig. 4. Schematic representation of the single basin solar still with water flowing over the glass.

S.A. Lawrance et al. [12,13] indicated from their results, the effect of water flow over the glass cover has a significant effect at large heat capacity of water mass in the basin. Y.P. Yadav and Ashok Kumar [14] studied the performance of a single basin solar still with water flow in the basin (Fig. 5). The authors found that, the water temperature, distillate output and efficiency of the system increases with decreasing mass flow rate and the optimum value of the mass flow rate through the basin of the still is 0.00027 kg/m^2 s.

M.S. Sodha et al. [15] conducted an experimental study of solar still with waste hot water from thermal power plants, their results showed that, the still fed with hot water at constant rate gives higher yield in comparison to a still with hot water filled only once in a day. G.N. Tiwari et al. [16] concluded from their detailed analysis, (i) with the flow of waste hot water during off-sunshine hours, will have higher yield than the stationary water, (ii) the yield increases in proportion to the increase in inlet water temperature during the flow of water, (iii) the still productivity increases with the increase in mass flow rate for higher inlet water temperatures and decreases for inlet water temperature less than the average ambient temperature, (iv) the still productivity is better for the waste hot water flow during off-sunshine hours than the continuous flow of hot water for lower inlet water temperature.

3.4. Double condensing chamber

G.N. Tiwari et al. [17] conducted an experimental analysis of a new design of double condensing chamber single basin single slope solar still. The authors concluded that, significant enhancement in daily output due to a maximum vapor pressure difference between the two condensing chamber on a clear day, (ii) the performance of double condenser chamber solar still gives a higher daily output of about 35–77% over the Conventional solar still.

3.5. Solar still with internal heat exchanger

Basin water temperature is one of the parameters to increasing the productivity of the still. By providing heat exchanger inside still and flowing waste hot water from various power plants, industries, etc., through the heat exchanger, can increase the basin water temperature. Ashok Kumar and G.N. Tiwari [18] studied the effect of inlet temperature of waste hot fluid, temperature dependence of internal heat transfer in a double slope single basin solar still with heat exchanger (Fig. 6). The results show that, the internal evaporative heat transfer is a strong function of the initial water temperature of the waste hot water.

3.6. Solar still with absorbing medium

Some of the materials can store more amount of heat energy and increase the heat capacity of the basin in addition to increasing

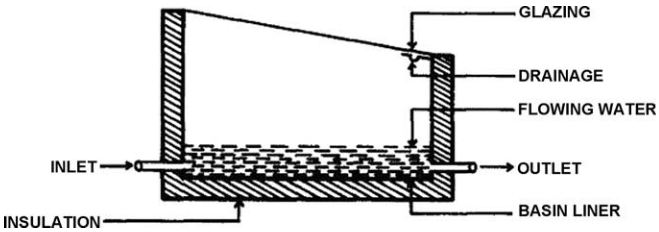

Fig. 5. Schematic of a single basin solar still with water flow in the basin [14].

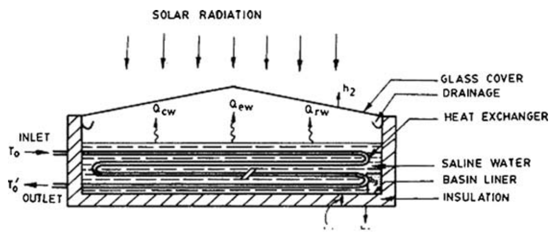

Fig. 6. Schematic representation of double slope single basin solar still with heat exchanger [18].

the basin absorption. Black rubber, gravels and aluminum sheet are some materials having these properties. P. Valsaraj [19] conducted an experimental study of single basin still with floating absorber aluminum sheet over the water surface. The result indicated that, the floating absorber sheet improves the output of the still compared to an ordinary conventional still. M. Sakthivel and S. Shanmugasundaram [20] studied the effect of black granite gravel (Fig. 7) as a storage medium and found that, the still yield is increased 17–20% compared with conventional still.

3.7. Wick type solar stills

A conventional basin type solar stills has some disadvantages, (i) the horizontal surface of water intercepts lesser solar radiation than a tilted surface. (ii) The output of basin type solar is also limited by the large thermal capacity of the water in the basin. A multi wick solar still (Fig. 8) is the best alternative for eliminating the above mentioned points. In which blackened wet jute cloth forms the liquid surface which can be oriented to intercept maximum solar radiation and a smaller mass of water will be heated to higher temperature and will evaporate rapidly. The wet surface is created by a series of jute cloth pieces of increasing length separated by thin polythene sheets, these pieces are arranged along an incline and the upper edges are dipped in a saline water tank. Suction by the capillary action of the cloth fibre, provides a surface of the liquid and the arrangement ensures that all the surface, irradiated by the sun is wet at all times; the portion of a piece of cloth, covered by the polythene sheet does not suffer evaporation and hence the exposed portion of the piece retains wetness [21].

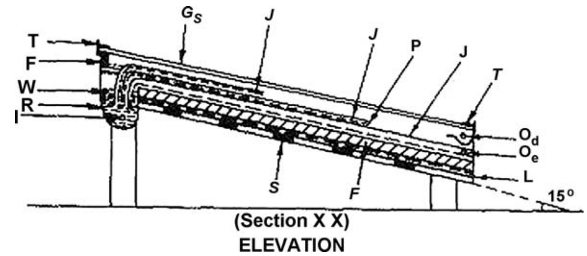

Fig. 8. Schematic representation of wick type solar still [21].

M.S. Sodha et al. [21] observed that, overall efficiency of multiple wick solar still is 4% higher than the basin type still. Their results also show that, the still cost less than half of the cost of a basin type still of same area and provide a higher yield of distillate. G.N. Tiwari and H.P. Garg [22] also confirmed that, the multiple wick solar still is the most economic and efficient among the existing solar stills. M.S. Reddy et al. [23] showed that, a multiple solar still with a condenser arrangement gives 15–25% higher than the non-condenser type still. The excess vapor can be condensed on the additional surface and reduce the heat loads on the glass cover and reduces glass-cover temperature which in turn enhances evaporation rate. This concept has implemented by G.N. Tiwari et al. [24] on multi wick solar still. The authors concluded that, the double condensing, multiple wicks solar still gives nearly 20% higher yield than the simple wick solar still and under cloudy and low intensity conditions both stills show almost a similar performance. N.K. Dhiman and G.N. Tiwari [25] indicated that, multiple wick solar still yield increased by 10%, when water is flowing over the glass cover in a very thin layer.

3.8. FRP solar stills

The cross-sectional view of the single slope Fibre Reinforced Plastic (FRP) solar still is shown in Fig. 9. A novel feature in this type of still is the absence of insulation on the sides and bottom. The advantages of the FRP stills are long life expectancy of at least 10 years, easy to handle and absence of any kind of insulation.

G.N. Tiwari et al. [26] and Y.P. Yadav and G.N. Tiwari [27], from their experimental study, concluded that, in winter the single slope

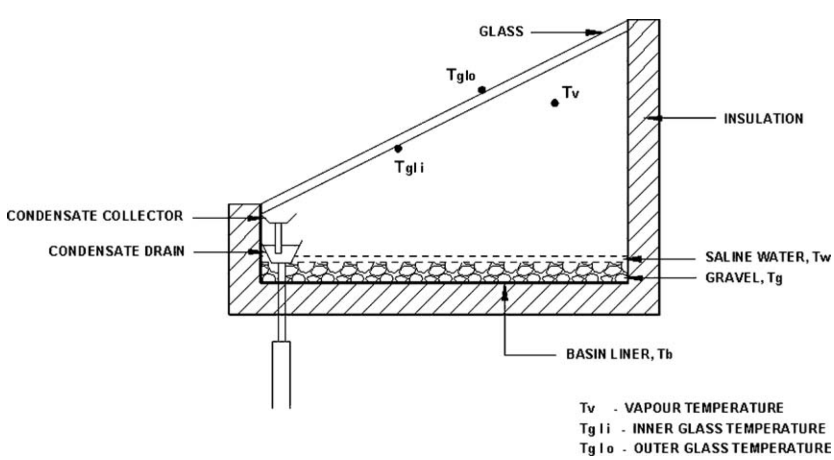

Fig. 7. Sectional view of the solar still with gravel [20].

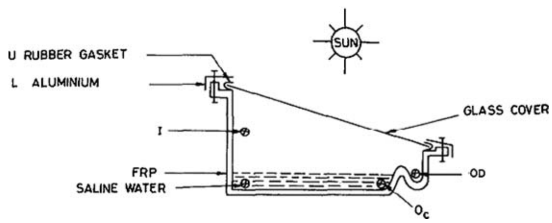

Fig. 9. Cross-sectional view of single slope FRP still [26].

FRP still gives better yield than the double slope stills, in summer the double slope stills gives better yield than the single slope still. G.N. Tiwari and G.A. Mohamed selim [28], showed that, a double slope FRP multi wick solar still is more economical and efficient than a simple one. A.K. Singh and G.N. Tiwari [29] have studied a double effect multi wick solar still (Fig. 10) with water flow into the basin. The results show that (i) double effect distillation is more efficient at the low flow velocity required in the wick solar still (ii) overall thermal efficiency decreases with an increase of mass flow rate.

3.9. Multi basin solar stills

The thermal efficiency of a solar distillation unit in terms of daily production per square meter can be increased by the utilization of the latent heat of condensation. The re-utilization of latent heat in two or more basins is generally known as a multi basin solar still. A schematic of a double basin solar still is shown in Fig. 11. In a double basin solar still, another glass sheet is fixed in between the basin liner and the glass cover. This glass sheet serves as the base of an extra basin for the saline water, and the whole assembly behaves as two simple basin solar stills placed one above the other. The water in the upper basin makes use of the upward heat loss by the water in the lower basin.

R.A. Gupta et al. [30] studied the effect of waste hot water into the lower basin at a constant rate (Fig. 12) during off-sunshine hours. The results show that, the yield increases with flow rate if the inlet waste hot water temperature is above its optimum value and the yield also decreases with a increase of water mass in the lower basin.

D.K. Dutt et al. [31] studied the effect of dyes in to the basin water. They observed that, an addition of dye increases the daily productivity and the efficiency of the system by about 10%. Ashok Kumar [32] observed that, the double basin solar still (Fig. 12) gives better performance than the single basin still due to better utilization of latent heat of vaporization. D.K. Dutt et al. [33] studied the effect of water flowing over the glass cover in the double basin solar still (Fig. 13). The authors concluded the flow of water over the glass cover enhances the still productivity and also flowing water at a very low rate increases the distillate output.

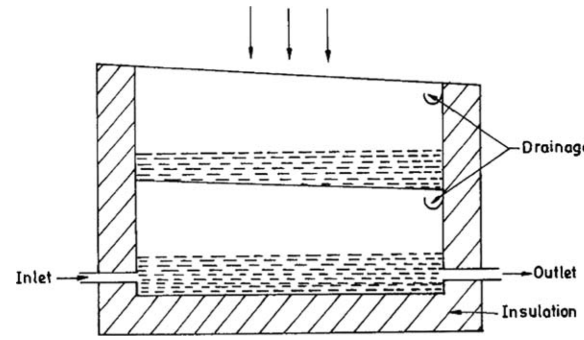

Fig. 11. Double basin solar still with constant flow rate [30].

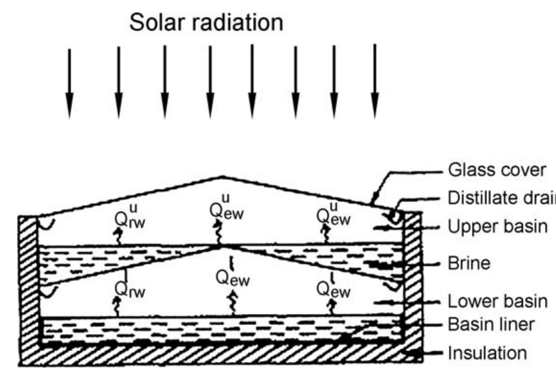

Fig. 12. Schematic of a double slope–double basin solar still [32].

3.10. Inverted absorber solar still

The schematic diagram of inverted absorber solar still is shown in Fig. 14. The solar radiation, after transmission through the glass cover g1, is reflected back to the inverted absorber of a solar still. The absorbed solar radiation is partially convected to the water mass above the inverted absorber; while the rest of the radiation is lost to the atmosphere through the glass covers g1 and g2. Now, the water gets heated. There are radiative, convective and evaporative heat losses from the water mass to the condensing cover. The evaporated water is condensed on the inner surface of the

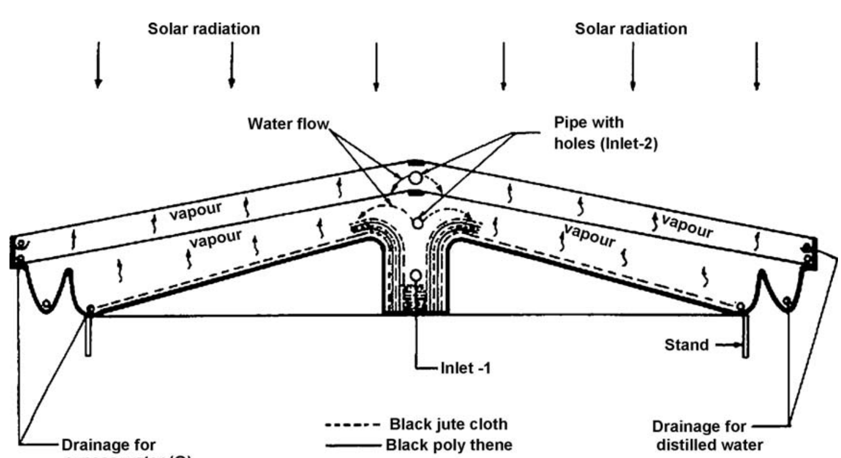

Fig. 10. Cross-sectional view of the double effect multi wick solar still [30].

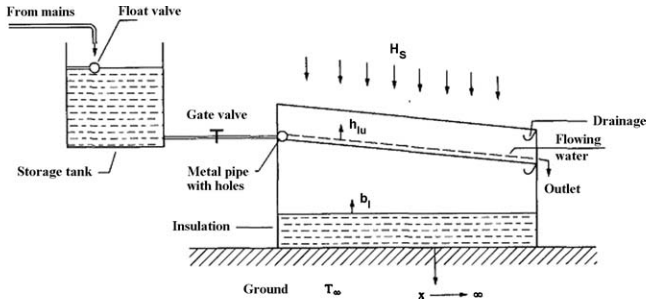

Fig. 13. Schematic representation of the double effect solar still with water flowing over the lower glass cover [33].

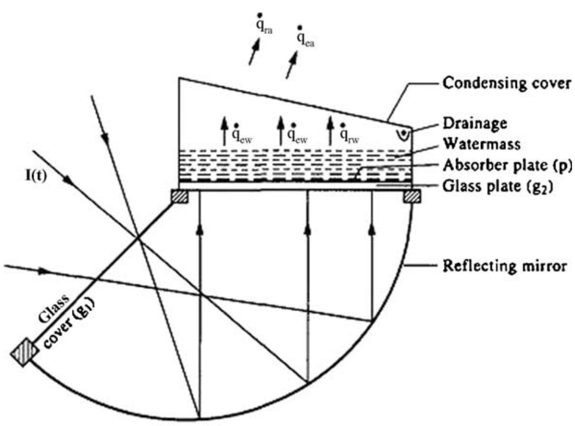

Fig. 14. Schematic diagram of inverted absorber solar still [34].

condensing cover, releasing its latent heat. The condensed water trickles down the condensing surface under gravity and is finally collected through drainage provided at the lower end [34].

G.N. Tiwari and Sangeeta Suneja [34,35] presented an analysis of an inverted absorber solar still. Their results show that, the inverted absorber solar still gives about double the output of the conventional solar still, also the authors observed that, the evaporative heat loss is a strong function of the operating temperature. Sangeeta Suneja et al. [36] also observed that, an inverted absorber solar still gives a higher output than the conventional double effect solar still. The overall daily yield in the case of the inverted triple effect absorber solar still is 30% higher than the conventional triple effect solar still [37]. Sangeeta Suneja and G.N. Tiwari [38], optimizing the number of effect on the multi basin solar still. They found that the yield from inverted absorber solar stills increases as the number of basins increased ad reaches an optimum value when the number of basin is seven. The operation and maintenance expenses of inverted double basin solar still are small compared with the conventional solar system [39].

3.11. Other type of passive solar still

3.11.1. Tubular solar still

The tubular solar still design consists of a rectangular black metallic tray placed at the diametric plane of a cylindrical glass tube. The length and diameter of the glass tube are slightly greater than the length and width of the tray, respectively. During operation, the ends of the glass tube are sealed with gasketed wooden heads. The tray and glass tube are fixed slightly tilted from the horizontal plane but in opposite directions. Brine fed from one end is partly evaporated, and the remainder discharged through the other end of the tube. The evaporated water condensed on the inside walls of the glass cover flows down and is removed from one end at the bottom of the glass tube (Fig. 15). The feed brine flow rate may be controlled by varying the location of the overflow hole of the flow control tank [40].

G.N. Tiwari [40] studied the performance of a tubular solar still for nocturnal production based on the effect of brine flow, still length, initial brine temperature and other climatic conditions. Based on the analysis, concluded that, (i) the average brine temperature is independent of still length for higher flow rate while the output temperature of brine strongly depends on still length, (ii) the daily yield of distillate in the tubular solar still is higher than that of the conventional solar still.

3.11.2. Tubular multi wick solar still

A schematic representation of tubular multi wick solar still is shown in Fig. 16. The design of a tubular multi wick solar still may be considered to be the combination of tubular and multi wick solar stills. The simple tray-type basin of the tubular solar still has been replaced by a G.I. or FRP tray containing a black colored jute cloth of the same size and lying along an incline, with the upper edge dipped in the saline water reservoir. Outlets for excess and condensed water are arranged as shown in Fig. 16. The system is like a multi wick solar still placed inside the diametric plane of a hollow glass cylinder along its length. Suction due to capillary action of the cloth fibres creates a thin water film. Solar radiation is absorbed by the blackened wet jute cloth after transmission through the upper half of the cylindrical glass cover. The water in the jute cloth is heated and evaporation starts. Vapors after transfer of latent heat to the glass, are condensed and the condensate then trickles down to the lower end under gravitation. The water attains a much higher temperature compared to that for a large basin water mass on account of its very

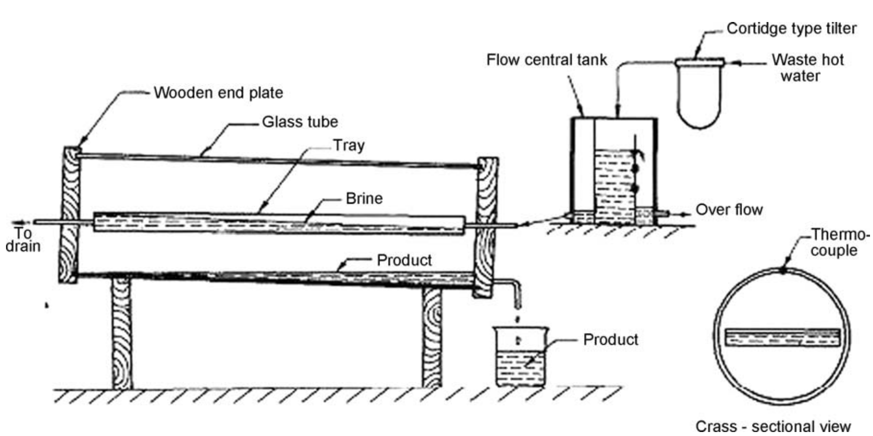

Fig. 15. Schematic representation of a tubular solar still [40].

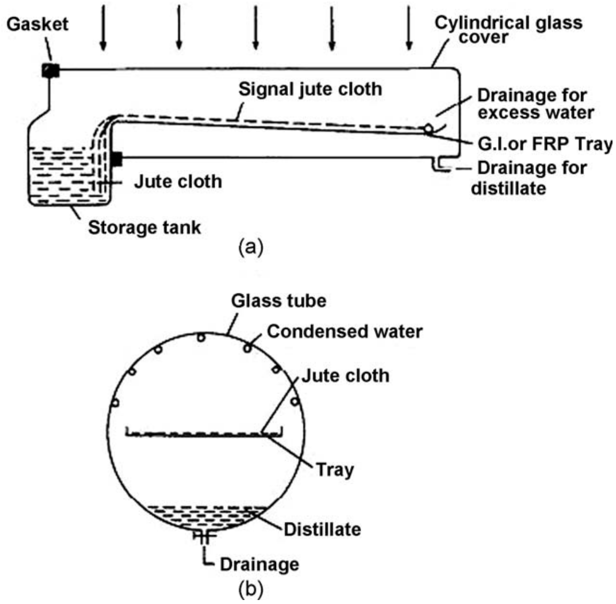

Fig. 16. Schematic representation of a tubular multi wick solar still; (a) side view and (b) front view [41].

low thermal capacity. Because of the curvature of the upper half of the glass cover, the condensing surface area is increased by more than 50% above that for a flat surface. As the result, there is faster heat loss from the glass cover, which increases the difference between water and glass-cover temperatures and hence the condensation rate [41].

3.11.3. Spherical solar still

The spherical solar still (Fig. 17) consists of a blackened metallic plate placed horizontally at the centre of a transparent envelope, which is spherical in shape and is usually made of glass. Naresh K. Dhiman [42] presented a mathematical model to predict the thermal performance of a spherical solar still. The results show that, spherical solar still efficiency 30% more than the conventional solar still.

3.11.4. Solar still integrated with greenhouse

A schematic diagram of a solar still-cum-greenhouse, indicating the solar energy absorbed by the roof and wall is shown in Fig. 18. The absorbed solar radiation by the basin liner is partially transferred to water mass, and the rest is transferred to a room by conduction, convection and radiation. The stored energy in the water causes evaporation, and it then condenses and ultimately

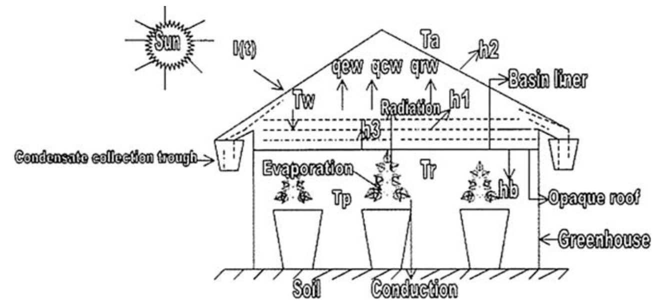

Fig. 18. A schematic view of a solar still-cum-greenhouse [43].

comes out in the form of fresh water to be used for irrigation purposes. The remaining transmitted solar energy is absorbed by the plants and the floor, after reflection. The absorbed energy is transferred to enclosed air by convection and radiation from the plant and floor; hence, room air is heated. A part of the energy absorbed by the floor is also conducted into the ground. If crops can be grown in strong sunlight without the debilitating effects of high temperatures, then high crop yields can be achieved with a significantly reduced consumption of water. [43]. N.S.L. Srivastava et al. [43] presented the performance evaluation of distillation cum greenhouse for a warm and humid climatic condition. Their result shows that, (i) there is a marginal difference between the values of plant and room temperature, water, transparent cover and basin liner temperatures also show a marginal difference, (ii) distillate output can be used as irrigation and greenhouse will provide the desired temperature to plant in a warm and humid climate in coastal regions. M.S. Sodha et al. [44] conducted experimental studies of roof type solar still and concluded that, in summer, the daily heat flux in the room gets reduced by 40% and in winter, mixed with black dye to obtain water, the daily heat flux in the room increased by a factor of two, productivity also increased.

3.11.5. Plastic solar still

M.K. Phadatare and S.K. Verma [45] conducted an experimental study the effect of water depth on the internal heat and mass transfer in a single basin single slope plastic solar still (Fig. 19). The plastic still was fabricated from Plexiglas. Based on experimental results, the authors concluded that (i) the maximum distillated output of 2.1 L/m^2/day was obtained with a water depth in a 2 cm still basin. (ii) The maximum efficiency of the experimental stills varies from 10% to 34%. It was found that the efficiency is maximum for a water depth of 12 cm.

3.12. Active solar distillation system

The productivity of the solar still also improved through active methods of integrating the still with either a solar heater, solar

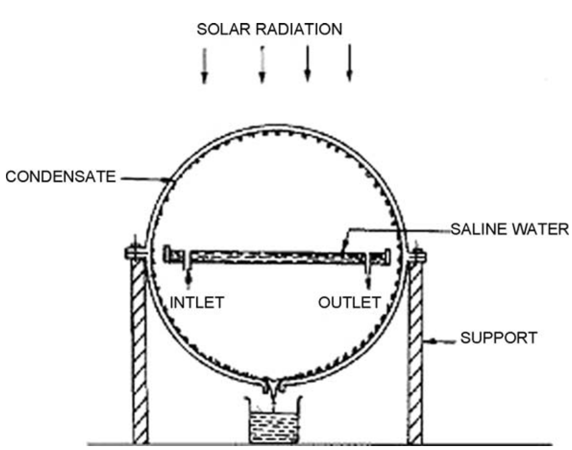

Fig. 17. Schematic of a spherical still [42].

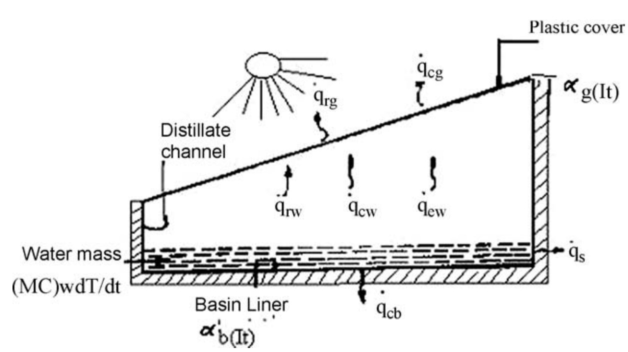

Fig. 19. Schematic of a plastic solar still [45].

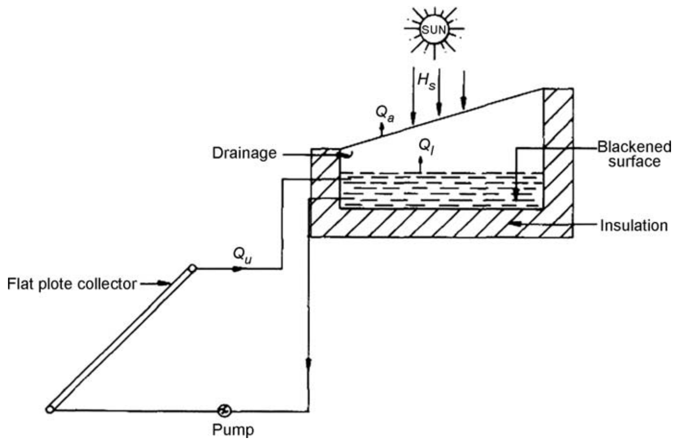

Fig. 20. Schematic diagram of single basin solar still coupled to flat-plate solar [46].

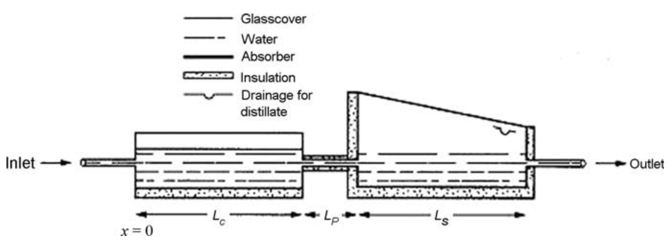

Fig. 21. Schematic diagram of single basin solar still coupled to parallel plate solar collector [54].

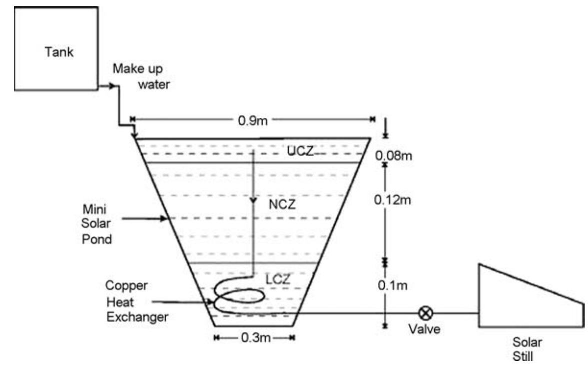

Fig. 22. Schematic diagram of the experimental set-up [55].

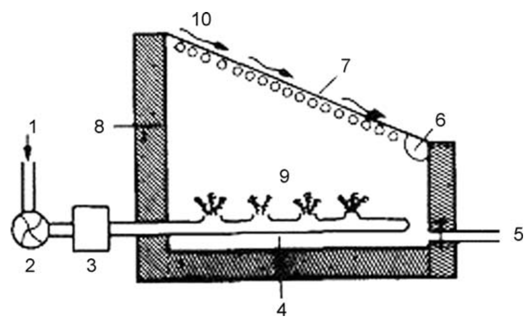

Fig. 23. Schematic diagram of air bubbled solar still [56].

concentrator or other heating devices. The blackened surface of the flat-plate collector absorbs solar radiation, and the liquid in contact with it gets heated. This heated liquid is circulated through the heat exchanger and it gives its heat to water in the still. The blackened bottom of the still also absorbs solar radiation that heats the water. The evaporation of water in the still starts, and when the air inside the still is saturated, the water vapor condense on the relatively cooler surface of the glass cover. The water droplets slide down under gravity to the drainage. The circulation of water through the flat-plate collector obtain either using pump (active mode) or by thermosiphon operation (natural circulation mode). S.N. Rai and G.N. Tiwari [46], presented the performance of a single basin solar still coupled with a flat-plate collector (Fig. 20). The results show that, the average daily production of distilled water has been found to be 24% higher than for a simple single basin solar still. S.N. Rai et al. [47] concluded that, the best performance will be the single basin still coupled with a flat-plate collector having forced circulation and blackened jute cloth floating over the basin water and a small quantity of black dye added to the water and from the economy point of view, the circulating pump should be used in the morning and evening when thermosiphon stops during sunshine hours. Y.P. Yadav [48] studied the performance of a solar still integrated with a flat-plate collector using a thermosiphon mode of operation and compared with forced circulation mode. The authors concluded that (i) the system using the forced circulation mode gives 5–10% higher yield than that of the thermosiphon mode. (ii) A 30–35% enhancement in the yield is observed with the proposed system as compared to the conventional system.

G.N. Tiwari [49] concluded, for higher daily yield, the collector should be disconnected from the still during off-sunshine hours. G.N. Tiwari and N.K. Dhiman [50] indicated, for drinking purpose, the conventional still will give better performance because the efficiency of the system reduces with an increase in the effective area.

Sanjeev Kumar, G.N. Tiwari [51] found that, the optimum collector inclination is 20° and the still glass-cover inclination is 15°, for maximum annual yield of the solar still. H.N. Singh, G.N. Tiwari [52] based on their detailed analysis concluded, the annual yield is at its maximum when the condensing glass-cover inclination is equal to the latitude of the place and the optimum collector inclination for a flat-plate collector is 28.58° for a condensing glass-cover inclination of 18.58° for New Delhi climatic conditions. Rajesh Tripathi, G.N. Tiwari [53] observed that, more yield is obtained during the off shine hours as compared to day time for higher water depths in solar still due to storage effect. Y.P. Yadav and A.S. Prasad [54] presented a performance analysis of a solar still integrated with a parallel flat-plate solar collector (Fig. 21). They indicated, parallel plate collector also able to increase basin water temperature higher than 50 °C.

V. Velmurugana, K. Srithar [55] conducted experimental analysis of a mini solar pond assisted solar still (Fig. 22) with sponge cube. The results show that, the average daily production of distilled water increased considerably while the sponged solar still is integrated with a mini solar pond. G.C. Pandey [56] presented the effect of bubbling of ambient air and cooling of the glass cover (Fig. 23). The author concluded, the efficiency of the still increased by dry air bubbling and glass cooling. S.K. Singh et al. [57] presented an analytical expression for the water temperature of an active solar distillation unit with collectors and concentrator

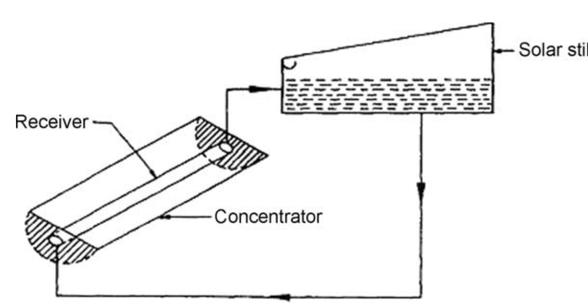

Fig. 24. Cross-sectional view concentrator assisted solar distillation system [57].

(Fig. 24). The result shows the efficiency of the system with a concentrator is higher than that with a collector.

4. Economic analysis of solar still

The value of a solar still must ultimately be judged on the basis of its economy. As is evident by now, solar stills are characterized by high initial costs. However they bring long term benefits in the form of lower annual operating costs. An economic evaluation of a solar still has to consider both these aspects. Considering the initial investment in any solar energy system to be P with the annual interest rate on such capital being (r) in percentage, and (n) being the number of useful years for which the system will perform, then,

$$\text{Capital recovery factor (CRF)} = \frac{r(1+r)^n}{(r+1)^n - 1}$$

Hence, the first annual cost of the system (AC) = (CRF) P. Again, if the salvage value of the system is taken as (S), since the sinking fund factor (SFF) is given by

$$\text{SFF} = \frac{r}{(1+r)^n - 1}$$

The annual salvage value = (SFF) S.

As the system will also require some annual maintenance, the annual cost of the system, incorporating the annual maintenance cost, will be given by

$$\begin{aligned}\text{Annual cost} &= \text{first annual cost} + \text{annual maintenance cost} \\ &\quad - \text{annual salvage value}\end{aligned}$$

If 'Y' be the annual yield of the system, and 'A' be the area of still, then,

(i) Product cost per liter = AC/Y.
(ii) Annual cost per m^2 = AC/Y.
(iii) Yield per rupees = Y/AC.

K. Mukherjee ad G.N. Tiwari [58] studied the cost analysis of different types of stills, and recommended that, cost of distilled water production from FRP still is lower than the G.I. body stills and roof type concrete solar distillation plants are best choice for large scale plants. Y.P. Yadav and G.N. Tiwari [59] concluded the cost of distilled water is economically more viable than that obtained from the conventional system.

5. Research and recommendations

A review of factor influencing the total efficiency shows that there are some major aspects which appear to control the future trends of solar desalination. Research should be directed towards the identification of the combination of the following design and operational parameters in future developments in solar distillation systems: (a) Lower cover temperature (cover cooling, multi effect, additional condenser, etc.). (b) Higher basin temperature (lower water capacity in the basin, use of wick, adding various dyes, additional external heating—collector, concentrator, waste heat recovery, overnight with basin energy storage, etc.). (c) Minimize heat losses from wall sides (good insulation). (d) Re-utilization of the latent heat of condensation (multi effect). (e) Large evaporation and condensation surface areas. (f) Economic analysis of solar distillation system—although many researchers were very much concerned with increasing the still's efficiency and productivity, not much cover the economical considerations of theses development so as to assess the ultimate cost of product water. Continuous research will ultimately lead to a water production cost that can compete with other technologies. Larger distillation units will help the overhead costs of common and auxiliary systems and components to have a smaller effect on the water production cost.

6. Conclusion

On the basis of discussion in various sections, the following conclusions can be inferred:

- Solar energy is abundant, never lasting, available on site with free of cost and pollution free energy;
- Solar distillation is the best solution for remote areas and small communities in arid and semi-arid regions with lack of water; Reasonable chances for success of full application of solar stills exist in places where (a) the unit is suitable regarding water resources, (b) there is a general involvement of users in the operation and maintenance and (3) good social and political organizational structure for operating, maintaining and repair exist.
- Solar stills have a good chance of success in India for lower capacities which are more than 20 km away from the source of fresh water and where the TDS of saline water is over 10,000 ppm;
- A single sloped solar still receives more radiation than a double sloped solar still at low and high altitude stations;
- The effect of water flow over the glass cover has a significant effect at large heat capacity of water mass in the basin;
- The floating absorber sheet improves the output of the still compared to an ordinary conventional still;
- The multiple wick solar still is the most economic and efficient among the existing solar stills;
- The double condensing, multiple wicks solar still gives nearly 20% higher yield than the simple wick solar still;
- An addition of black dye increases the daily productivity and the efficiency of the system by about 10%;
- The overall daily yield in the case of the inverted triple effect absorber solar still is 30% higher than the conventional triple effect solar still;
- The daily yield of distillate in the tubular solar still is higher than that of the conventional solar still;
- Solar stills in combination with greenhouses could be designed to provide technically feasible systems suitable for arid areas.
- In active solar distillation system the optimum flat-plate collector inclination is 20° and the still glass-cover inclination is 15°, for maximum annual yield of the solar still;
- Economic point of view roof type concrete solar distillation plants are best choice for large scale plants.
- To decrease fresh water costs, efforts should be undertaken on the following research topics; thermal storage studies, insulation studies, thermo-optical studies for the condensing covers, geometry and design studies.

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